

Bounds on the neutrino flux from cosmic sources of relativistic particles

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Abstract. In order to facilitate the identification of possible new physics signatures in neutrino telescopes, such as neutrinos from the annihilation of neutralinos or decaying relics, it is essential to gain full control over the astrophysical inventory of neutrino sources in the Universe. The total available accretion power, the extragalactic gamma ray background, and the cosmic ray proton intensity can be used to constrain astrophysical models of neutrino production in extragalactic sources. The resulting upper limit on the extragalactic muon neutrino intensity from cosmic particle accelerators $F_{\nu_\mu,\text{u.l.}} \approx 10^{-6} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ combined with a reasonable minimum intensity of neutrinos due to cosmic rays stored in clusters of galaxies $F_{\nu_\mu,\text{min}} \approx 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ demarcate a zone of opportunity for neutrino astronomy over a broad range of energies between 100 MeV and 1 EeV. Discovery of this neutrino background would open a new era for astronomy and provide the first un-obscured view to the early Universe.

1. Introduction

Surveying the sky with new instruments and methods has many times prompted discoveries in the history of physics. A well-known example is the sky survey obtained by Tycho Brahe during 1576-1596, unprecedented in terms of accuracy, scope, and sensitivity at his time, which lead to Kepler's 1601-1619 discovery of the elliptical planetary orbits and the three laws describing them. This discovery paved the way to Newton's 1664 theory of gravitation based on the notion of an absolute metric space. Another example is the work of Charles Messier who compiled a catalogue of nebular objects during 1771-1784 to increase the finding probability for comets. Edwin Hubble proved in 1925 that among these sources were indeed galaxies gravitationally unbound to the Milky Way initiating extragalactic astronomy and observational cosmology.

Electromagnetic waves, covering the electromagnetic spectrum from radio waves to gamma rays, play the leading role in modern astronomy due to their easy detection and diagnostic potential. Other carriers of information are stable particles emitted from cosmic sources, such as protons, ions, electrons, and neutrinos. The cosmic ray protons,

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ions, and electrons can be detected with great sensitivity, and studies of their interactions in the Earth's atmosphere have lead to a large number of discoveries in elementary particle physics, the latest of which is the discovery of neutrino mass from the deficit of large zenith-angle muon neutrinos (Fukuda et al. 1998). Cosmic rays are useless as astrophysical probes, however, due to the omnipresence of interstellar and intergalactic fields which deflect them away from the direction of the sources. The exploration of the high-energy Universe therefore relies on radio astronomy, which is sensitive to the synchrotron radiation from accelerated electrons, and gamma-ray astronomy, which probes hadronic interactions of accelerated baryons and inverse-Compton scattering and bremsstrahlung from accelerated electrons. However, the mean-free-path for gamma rays decreases to less than the distance to the Galactic Center at energies above a few hundred TeV due to pair creation, and most of the Universe remains unseen. Ultimately, photons do not penetrate the cosmic photon-matter barrier making the first 10,000 years in the history of the Universe invisible.

Neutrino astronomy (Gaisser et al. 1995, Halzen 2000, Learned and Mannheim 2000) can provide an un-obscured view to the Universe, and neutrino detection is eased at high energies due to

- (i) the increasing neutrino-matter interaction cross section and muon range,
- (ii) the large natural water (or ice) reservoirs transparent to the Cherenkov light produced in charged current interactions, which can be used for neutrino-induced muon and shower detection,
- (iii) the steeply decreasing local foreground fluxes, and
- (iv) the fascinating physics potential at high energies (e.g., the neutralino with a mass of the order of the electroweak symmetry breaking scale $\frac{1}{2}(\sqrt{2}G_F)^{-1/2} \simeq 123$ GeV is one of the most favored candidates for the prime component of cold dark matter and annihilations such as $\chi\bar{\chi} \rightarrow W^+W^-$, $b\bar{b}$, and $Z\gamma$ would lead to observable neutrinos).

However, until the time of writing, no extraterrestrial > 100 MeV neutrino has been discovered presumably due to the effective areas in the running experiments being still too small for a detection. In order to set the scale for experimentally reaching a zone of discovery, theory attempts to provide a first estimate of the expected total high-energy neutrino intensity due to conventional astrophysical sources, as has been done e.g. by Stecker et al. (1996), Mannheim (1995), Protheroe & Johnson (1996), Waxman and Bahcall (1998), and Mannheim et al. (2000). Rarely in the history of science has such a first estimate been close to reality. For example, X-ray astronomy was considered a useless enterprise in the 50s, when it was known that stars had surface temperatures not exceeding 10^4 K. With X-ray astronomy came the discovery of accreting stars, unexpected by most astrophysicists, which release gravitational rather than nuclear energy at an enormous rate. Nevertheless, the attempt seems well justified, since

a measured flux greatly deviating from the predicted range of fluxes would readily indicate a theoretical deficit prompting new developments. In the following sections, possible routes to bounding the allowed neutrino flux for models of extragalactic neutrino production are outlined.

2. Accretion power bound

The dominant sources of relativistic particles in the Universe are supermassive black holes in the centers of galaxies. Since bright galaxies generally contain supermassive black holes in their center with a mass proportional to the mass concentrated in their stellar bulges (Rees and Silk 1998, Gebhardt et al. 2000), it is possible to make a cosmic census of all such black holes by using the well-known galaxy luminosity function. Moreover, since the mass in black holes was acquired through accretion, one can estimate the total accretion power released in the Universe (Fabian 1999, Mannheim 1999).

Heavy elements with present-day mass fraction $Z = 0.03$ were produced in early bursts of star formation by nucleosynthesis with radiative efficiency $\epsilon = 0.007$ yielding the present-day omnidirectional stellar-light intensity

$$I_{\text{ns}} \sim \frac{c}{4\pi} \frac{\rho_* Z \epsilon c^2}{1 + z_f} \quad (1)$$

where ρ_* denotes the mass density of baryonic matter and z_f the formation redshift corresponding to the era of maximum star formation (the ratio between the energy released by stars and by other sources with the same formation history is independent of its details). Let Ω_* denote the baryon density in terms of the critical density of the Universe and $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ the dimensionless Hubble constant, then the intensity obtains the value

$$I_{\text{ns}} \sim 1.4 \times 10^{-2} \left(\frac{\Omega_* h^2}{0.01} \right) \left(\frac{1 + z_f}{4} \right)^{-1} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \quad (2)$$

and this is in agreement with the observed intensity of the integrated extragalactic background spectrum from the far-infrared to the ultraviolet. Bright galaxies containing supermassive black holes in their centers which are actively accreting over a fraction of $t_{\text{agn}}/t_* \sim 10^{-2}$ of their lifetime produce an accretion-light intensity

$$I_{\text{accr}} \sim \frac{\epsilon_{\text{accr}} M_{\text{bh}} t_{\text{agn}}}{Z \epsilon M_* t_*} I_{\text{ns}} \sim 3.3 \times 10^{-4} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (3)$$

adopting the accretion efficiency $\epsilon_{\text{accr}} = 0.1$ and the black hole mass fraction $M_{\text{bh}}/M_* = 0.005$. Most of the accretion power emerges in the ultraviolet where the diffuse background is unobservable owing to photoelectric absorption by the neutral component of the interstellar medium. However, a fraction of $I_x/I_{\text{bh}} \sim 20\%$ taken from the average quasar spectral energy distribution (Sanders 1989) shows up in hard X-rays consistent with the observed hard X-ray background bump $I_x \sim 6.0 \times 10^{-5} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (Gruber 1992). Non-thermal emission shows up only in the radio-loud fraction $\xi_{\text{rl}} \sim 20\%$

of all AGN. Among the radio-quiet AGN, hard X-ray emission is common, but turns over steeply below 100 keV with no signs for a nonthermal component. The kinetic power of the jets in radio-loud AGN responsible for the nonthermal emission roughly equals the accretion power (Rawlings and Saunders 1991). Hence one obtains for the nonthermal intensity due to extragalactic jets

$$I_j = \left(\frac{\xi_{rl}}{0.2} \right) I_{accr} \sim 6.7 \times 10^{-5} \left(\frac{\xi_{rl}}{0.2} \right) \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}. \quad (4)$$

This energy is released in relativistic particles, magnetic fields, and pdV thermodynamic work against the ambient medium into which the jets propagate. The gamma ray (cosmic ray, neutrino) energy released by the jets amounts to the present-day intensity

$$I_\gamma \sim \xi_{rad} I_j \sim 6.7 \times 10^{-6} \left(\frac{\xi_{rad}}{0.1} \right) \left(\frac{\xi_{rl}}{0.2} \right) \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (5)$$

which is remarkably close to the intensity $7.6 \times 10^{-6} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ of the extragalactic gamma ray background observed between 100 MeV and 30 GeV using the spectrum from Sreekumar et al. (1998) and a radiative efficiency of $\xi_{rad} = 10\%$. Note that the intensity in the observed gamma ray background is close to the bolometric gamma ray intensity, since pair attenuation and cascading must lead to a turnover of the background spectrum above 20–50 GeV for extragalactic source populations (Salamon and Stecker 1998).

It is therefore concluded, that if neutrinos tap a significant fraction of the total nonthermal accretion power available in the Universe, then their bolometric intensity cannot exceed the intensity of the extragalactic gamma ray background, even if gamma rays could not escape from the sources.

Since the observed black holes account precisely for the extragalactic X-ray background, hidden supermassive black holes and neutrinos from them (Berezinsky and Dokuchaev 2000) are unlikely to exist: they would have to lie outside of bright galaxies, and they would have to be heavily obscured at all times to avoid shining up in X-rays. It is also possible to invoke a scenario with hidden black holes which reside in an advection-dominated accretion mode from which only neutrinos escape.

3. Extragalactic gamma ray background bound

A more restrictive bound might apply for sources, from which the gamma rays co-produced with neutrinos during pion decay escape. The physical conditions inside typical nonthermal sources are characterized by a low matter density, indeed, since this is the prerequisite for efficient particle acceleration. The observed gamma rays are likely to be the result of electromagnetic cascading, taking place during intergalactic travel or still inside the sources. For typical extragalactic distances of the order of Gigaparsecs, gamma rays above 100 GeV are expected to be absorbed in collisions with

low-energy photons from the metagalactic radiation field produced by galaxies. The resulting electron-positron pairs re-radiate gamma rays by inverse-Compton scattering off microwave background photons primarily in the MeV-to-GeV band, adding to the primary radiation in this band. Therefore the observed extragalactic gamma ray background intensity (Sreekumar et al. 1998) represents an upper limit to the maximum electromagnetic energy release due to pion production applying proper corrections for the kinematic branching between neutrinos and gamma rays (Rachen and Mészáros 1998), e.g. $L_\gamma = 2L_\nu$ for jets in active galactic nuclei and $L_\gamma = L_\nu$ for jets in gamma ray bursts (due to the different slopes of the target photon spectra). Hidden sources, for which the escaping electromagnetic flux is reprocessed thermally to below the 100 keV range, are possible, but their total intensity must still remain below the accretion-related bound outlined in the previous section - unless these hidden sources would be related to an energy reservoir different from the supermassive black holes in the centers of galaxies.

4. Cosmic ray bound

The bound discussed in the previous section applies to extragalactic particle accelerators, from which there is no contribution to the observed cosmic rays due to escaping nucleons. If, however, ultrarelativistic nucleons escape and contribute to cosmic rays, the observed cosmic ray intensity can be used to constrain models of neutrino production.

Even in sources, in which the accelerated particles are fully confined (by magnetic fields), there is a flux of escaping neutrons produced in the common isospin flip interactions. Relativistic neutrons at ultrahigh energies have decay lengths $l_n \simeq 10(\gamma_n/10^9)$ kpc and leave the acceleration site and the host galaxy without adiabatic losses. The neutrino yield per escaping nucleon is highest comparing with other escape mechanisms, e.g. it could be lower if there were additional prompt protons escaping from the accelerator which are not accompanied by neutrinos. By the logic inherent to an upper limit, the discussion is restricted here to the case of neutron-origin cosmic rays.

An extragalactic flux of cosmic rays from evolving sources would be mostly protonic due to the photo-disintegration of heavy nuclei (Stecker and Salamon 1999). The observed upper limit on extragalactic protons can be converted to an upper limit on extragalactic neutrinos by virtue of the production and decay kinematics. This has been worked out in detail by Mannheim, Protheroe, and Rachen (2000) using a propagation code developed by Protheroe and Johnson (1996) and assuming an evolution of the comoving emissivity of the putative cosmic ray/neutrino sources given by

$$(dP_{\text{gal}}/dV_c)\langle Q(E, z) \rangle \propto (1 + z)^{3.5}, \quad (6)$$

which has the same redshift dependence as the cosmic star formation rate or the AGN emissivity (Boyle and Terlevich 1998). The cosmic ray intensity at Earth at energy E

due to neutron decay is given by

$$I(E) \propto \int_{z_{\min}}^{z_{\max}} M(E, z) \frac{(1+z)^2}{4\pi d_L^2} \frac{dV_c}{dz} \frac{dP_{\text{gal}}}{dV_c} \langle Q[(1+z)E, z] \rangle dz \quad (7)$$

where d_L and V_c are luminosity distance and co-moving volume, and $M(E, z)$ are “modification factors” for injection of protons at redshift z as defined by Rachen and Biermann (1993); for neutrinos, $M(E, z) = 1$. The modification factors for protons depend on the input spectra, and are calculated numerically using a matrix method (Protheroe and Johnson 1996). The trial functions for the spectra emitted by extragalactic photo-production sources with target spectral index $\alpha = 1$ (typical for conditions in jets from active galactic nuclei) are

$$Q_{\nu_\mu}(E) = 83.3 Q_n(25E) \quad (8)$$

and

$$Q_n(E) \propto E^{-1} \exp[-E/E_{\max}] \quad (9)$$

with variable E_{\max} . The construction of the upper limit now proceeds by first choosing a value for E_{\max} and finding the maximum source emissivity which does not overproduce either the experimental upper limit on cosmic ray protons or the observed extragalactic gamma ray background (comparing integrated fluxes because of electromagnetic cascading which destroys the proportionality between the differential spectra). Second, the neutrino intensity is computed for the maximum allowed emissivity at E_{\max} , and third, the envelope curve for a set of E_{\max} values then defines the upper limit (see Mannheim et al. 2000 for more details). The resulting upper limit is largely robust with respect to the specific spectral shape generated by a source distribution.

Below neutrino energies of $\sim 10^5$ GeV the constraint due to the observed cosmic rays becomes sharper than that due to the extragalactic gamma ray background. The upper limit decreases with energy reaching a minimum at around $\sim 10^9$ GeV. At higher energies, the upper limit increases for technical reasons: the observed cosmic rays show an excess above the so-called GZK cutoff which would require an emissivity increasing with energy in order to compensate the photo-hadronic energy losses due to propagation through the microwave background.

5. Neutrinos due to cosmic ray storage in clusters of galaxies

It was shown in Sect. 2 that the intensity in relativistic particles available through accretion is $\sim 6.7 \times 10^{-5}$ GeV cm $^{-2}$ s $^{-1}$ sr $^{-1}$. The supermassive black holes giving rise to radio jets preferentially lie in clusters of galaxies which contain an intracluster medium of gas density $n_c \approx 10^{-3}$ cm $^{-3}$ which acts as a target for the relativistic particles from the jets diffusing through the intracluster medium. The optical depth of this medium with respect to pion production is $\sim 9 \times 10^{-5}$, and, using $I_\gamma = I_\nu$, the corresponding minimum neutrino intensity due to cosmic ray storage is of the

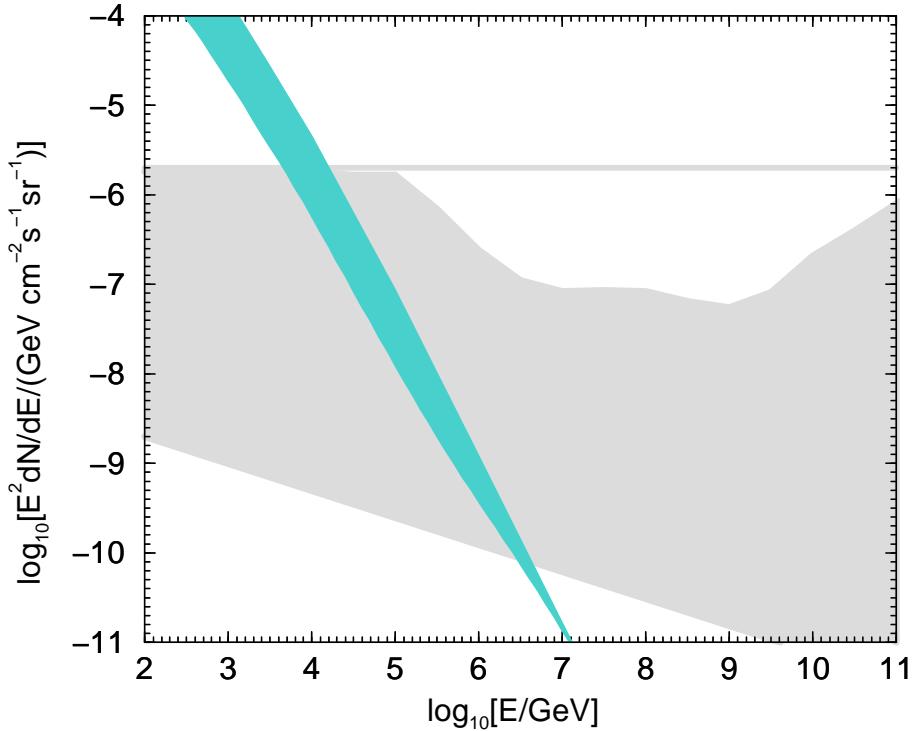


Figure 1. Upper limits on the extragalactic neutrino intensity based on (i) the extragalactic gamma ray background (*straight grey line*) and (ii) the observed cosmic ray intensity (*upper edge of gray shaded area*) ignoring the possible effects of large-scale magnetic fields. The *lower edge of the gray shaded area* depicts the lower limit due to cosmic ray storage in clusters of galaxies assuming that the nonthermal accretion power is channeled into a power-law distribution of protons. For comparison, the figure also shows the intensity of atmospheric neutrinos for directions from vertical to horizontal, including the omnidirectional contribution from prompt charm production estimated by Thunman et al. (1996) (*dark shaded area*).

order of $I_\nu \approx 3 \times 10^{-9}$ GeV cm $^{-1}$ s $^{-1}$ sr $^{-1}$. Outside of their sources, the stationary proton distribution should reflect the source distribution. For relativistic shocks, this distribution is expected to be $dN/dE \propto E^{-2.2}$ (Kirk et al. 2000), and the lower limit in Fig. 1 is normalized by the bolometric condition $\int_1^{10^{11}} E dN = I_\nu$ (E in GeV). The corresponding value $I_\gamma = I_\nu$ is consistent with upper limits on the gamma ray flux from clusters of galaxies and is in agreement with the much more detailed model of Colafrancesco and Blasi (1998).

6. Discussion

The presence of high-energy cosmic rays in extragalactic sources is inevitably associated with gamma rays and neutrinos. In principle, both cosmic ray nucleons and gamma rays could be absorbed in hidden sources, observable only in neutrinos. However, the

observed gamma-ray background can be attributed to the nonthermal fraction of the gravitational binding energy released during accretion of ambient matter onto supermassive black holes, and there is no other known energy reservoir available for hidden sources. If these putative sources tap a fraction of the nonthermal accretion energy of supermassive black holes, then this fraction must be very small, or there must exist heavily obscured supermassive black holes in great numbers outside of galactic centers which have escaped the cosmic census so far. Thus, an intensity in excess of the accretion bound would indicate this new population of black holes, or might indicate a new weak-channel dissipation process of the cold dark matter in the Universe.

The observed extragalactic gamma ray background is probably due to unresolved faint gamma ray point sources (associated with rotating supermassive black holes), since the known ~ 100 resolved sources above 100 MeV alone produce a cumulative flux amounting to ~ 0.15 of the total diffuse flux. We do not know much about the opacity for gamma rays in the sources, but their spectra generally do not seem to indicate a spectral turnover up to GeV energies. This translates into an opacity constraint for protons with respect to the photo-production on the same target photons and implies that these sources should typically be thin to the emission of cosmic ray nucleons up to $\sim 10^8$ GeV (corresponding to neutrino energies $\sim 10^6$ GeV). Since the optically thin limit approaches the gamma ray limit at energies of $\sim 10^5$ GeV, just a little effect due to large-scale magnetic fields raising the transition energy between the two limits to $\sim 10^6$ GeV (as argued in Mannheim et al. 2000, chapter V.) would likely render the gamma ray limit as the only conservative upper limit over the entire energy range. Future gamma ray observations could enhance the relevance of the cosmic ray bound, if it can be shown that the gamma ray spectra show no signs of intrinsic absorption up to energies much higher than GeV.

Some sources have been detected up to TeV without showing signs of internal absorption (albeit the steep multi-TeV spectra could indicate pair creation above TeV). These sources could be strong sources of neutrons (protons) up to 10^{11} GeV and the observed cosmic ray flux provides an upper limit to the allowed neutrino flux at $\sim 10^9$ GeV almost two orders of magnitude below the gamma ray limit. As shown in Mannheim (1995), a source population such as BL Lacertae objects, likely to produce a distribution of E_{\max} values, and saturating the cosmic ray bound at ultrahigh energies would nevertheless produce a significant fraction of the entire extragalactic gamma ray background (the bolometric gamma ray bound in a differential plot may be misleading in this case, since it is constructed for very hard trial spectra).

No gamma ray source is known to be definitely thin to the emission of cosmic rays above 10^{11} GeV. In principle, however, such a population could exist and could provide hard spectra of cosmic rays compensating the photo-production energy losses during passage of the microwave background with an emissivity strongly increasing with red-

shift. In this very unlikely case, the rising cosmic ray bound technically reflects the fact, that an excess of cosmic ray events has been found above the so-called GZK cutoff energy of 5×10^{10} GeV.

7. Conclusions

There are two arguments in favor of an extragalactic high-energy neutrino background bounded from above by the known intensity of the extragalactic gamma ray background and from below by the known matter column density of clusters of galaxies: naturalness and the likelihood of an extragalactic origin of the ultrahigh energy cosmic rays. It is natural to assume that a significant fraction of the nonthermal power produced by black holes is channeled into protons, since the transport of electrons out of the compact source region is strongly damped by radiative losses. The observed near isotropy and protonic character of the extended air showers at ultrahigh energies argues in favor of an extragalactic origin, and the gamma ray spectra from extragalactic jets are in accord with the assumption that protons are accelerated in them to ultrahigh energies (albeit there are competing explanations based on the assumption of electron acceleration, for thorough discussions see Mannheim 1998 and Wilson et al. 2000). The picture certainly needs experimental clarification by showing that extragalactic neutrinos with an intensity marked by the "zone of discovery" (the grey zone in Fig. 1) really exists. If a stronger intensity were found, this could imply a new population of completely obscured black holes outside of bright galaxies or a signature of relics from the Early Universe. If a weaker intensity were found, then extragalactic jets would not produce the ultrahigh energy cosmic rays, and accelerated protons would not be responsible for the observed gamma rays.

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